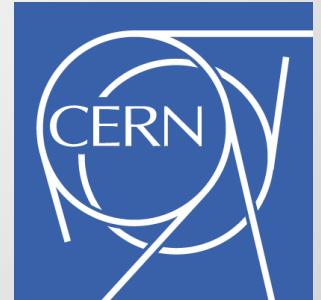


Recent constraints on axion-photon and axion-electron couplings with the CAST experiment



TAUP 2013
September, 2013. Asilomar, CA.

J. Ruz on behalf of the CAST Collaboration



LLNL-PRES-563700

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC



Outlook



- Axions:
 - Motivation, models, phenomenology and cosmology
- Solar axions: the CAST experiment
 - Detection of solar axions
 - The coherence condition
 - Results
 - Present data taking
- IAXO: the next generation
- Conclusions



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Axions: motivation, models, phenomenology and cosmology



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Axion motivation



- **Peccei-Quinn solution** to the strong CP problem
 - New U(1) symmetry introduced:
 - Peccei Quinn symmetry of scale f_a
 - The AXION appears as the **Nambu-Goldstone boson** of the spontaneous PQ symmetry breaking

"Axion lagrangian"

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} a G \tilde{G}$$

θ absorbed in
the definition of a



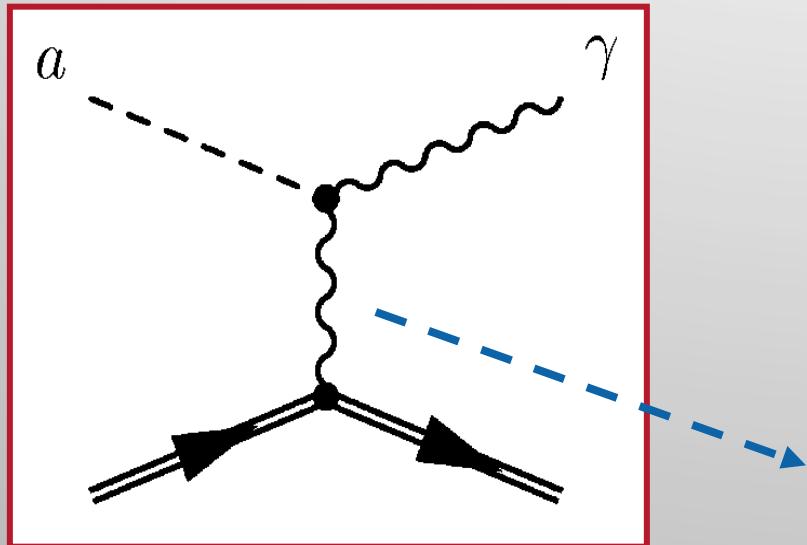
$\theta = a/f_a$ relaxes to zero...

CP conservation is preserved "dynamically"

Axion phenomenology



- **Axion-photon conversion** in the presence of an electromagnetic field (**Primakoff effect**)



This EM field can be

- an artificial magnetic field
- the Coulomb field of the plasma in the core of a star
- the periodic E field of a crystalline structure
- ...

Axion models



■ Axion decay constant

- The axion mass and the scale of the interaction are closely related

$$m_a = \frac{m_u + m_d}{\sqrt{m_u m_d}} \frac{m_\pi f_\pi}{f_a} = 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$$

$\boxed{z = 0.56} \quad \longleftarrow \quad z = \frac{m_u}{m_d} \subseteq [0.35, 0.6]$

- The nature of axion implies they must interact with hadrons and photons
 - Hadronic axion models
- GUT motivated axion models suggest that axions can also significantly interact with leptons
 - Non-hadronic axion models



Axion cosmology



- **Axions could be produced** in the early Universe by a number of processes:

- Axion realignment
- Decay of axion strings
- Decay of axion walls



NON-RELATIVISTIC
(COLD) AXIONS
Cold Dark Matter
(CDM) candidate

- Thermal production

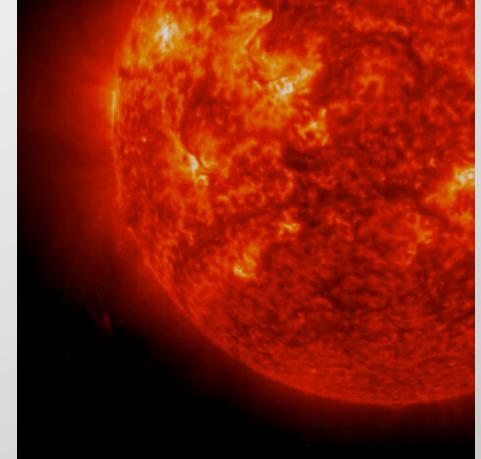


RELATIVISTIC
(HOT) AXIONS
Hot Dark Matter
(HDM) candidate

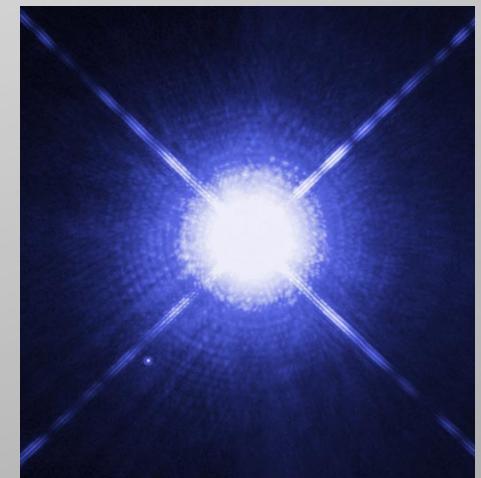
Axions in astrophysics



- Axions can be produced in the core of stars, like the Sun, by Primakoff conversion of plasma photons.



- Axion decay may produce γ -ray emission lines originating from certain places (e.g., galactic center).
- Axions may have a wider impact:
The cooling of white dwarfs



Classic axion searches



Laboratory axions

→ Shining-Light-through-Walls
(OSQAR, LIPSS, ALPS)

→ Polarization
(PVLAS)



Solar axions

→ Crystals
(SOLAX,COSME)

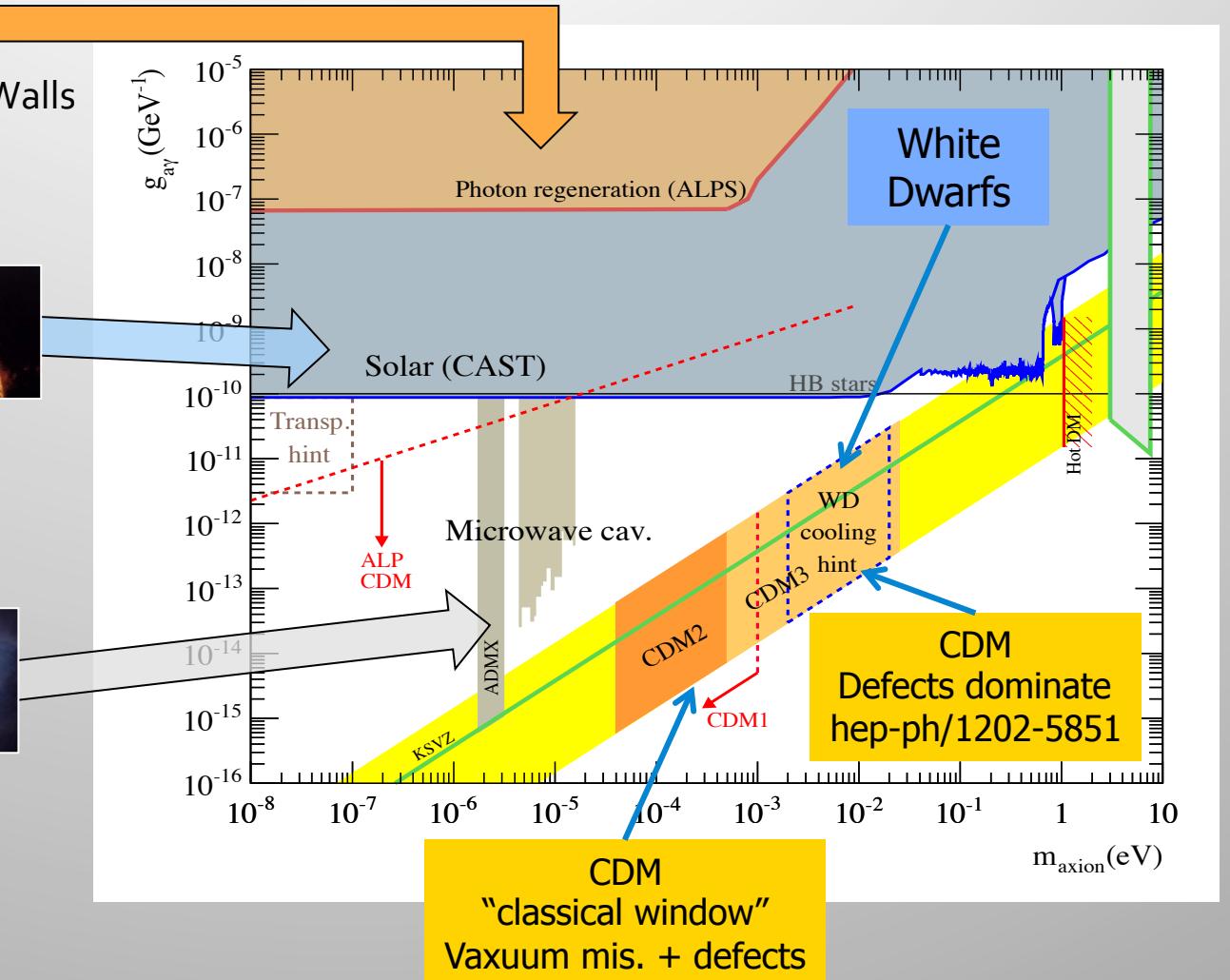
→ Helioscopes
(Tokyo, **CAST**)



Halo axions (relics)

→ Haloscopes
(ADMX,Carrack)

→ Telescopes
(Haystack)





Solar axions: the helioscope concept



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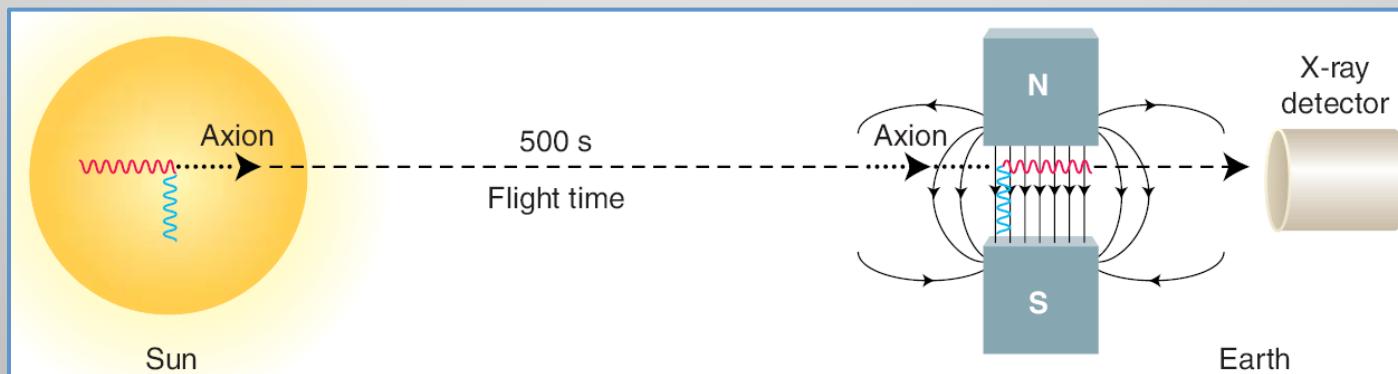
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Production and detection of axions

- First axion helioscope proposed by P. Sikivie Sikivie PRL 51:1415 (1983)
- Blackbody photons (keV) in solar core can be converted into axions in the presence of strong electromagnetic fields in the plasma
- Reconversion of axions into x-ray photons is possible in strong laboratory magnetic fields



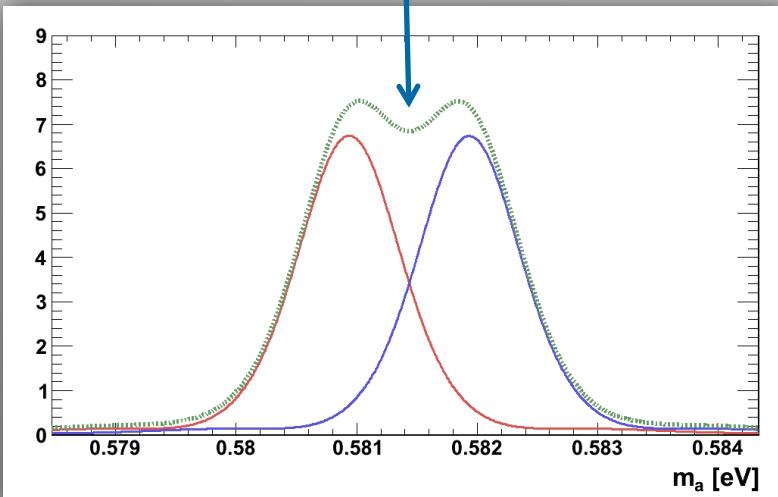
- Idea refined by K. van Bibber et al. by using buffer gas to restore coherence over long magnetic field Van Bibber et al. PhysRevD 39:2089 (1989)

Detection of solar axions



The axion mass band for which a Primakoff based experiment is sensitive can be extracted from the coherence condition

The converted photons may acquire an effective mass in the presence of gas extending the axion mass sensitivity range of an experiment that has a fixed magnet length



Conversion Probability

$$P_{a\gamma} = g_{10}^2 \times \left(\frac{B_\perp}{2}\right)^2 \frac{1}{q^2 + \Gamma^2/4} \left[1 + e^{-\Gamma L} - 2e^{-\Gamma L/2} \cos qL\right]$$

Coherence Condition

$$\left(\frac{m_a^2}{keV^2}\right) \ll \left(\frac{m_\gamma^2}{keV^2}\right) + 2 \left(\frac{E_a/keV}{L \cdot keV}\right)$$

Axion-to-photon conversion in the presence of a nearly homogeneous magnetic field \mathbf{B} is only effective when the polarization plane is parallel to the incident particle



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CAST experiment @ CERN

- Decommissioned LHC test magnet (L=10 m, B=9 T)
- Moving platform $\pm 8^\circ$ V, $\pm 40^\circ$ H (allows 3 hours/day of solar tracking)
- 4 magnet bores to look for x-rays from axion conversion
- X-ray focusing system to increase signal/background ratio



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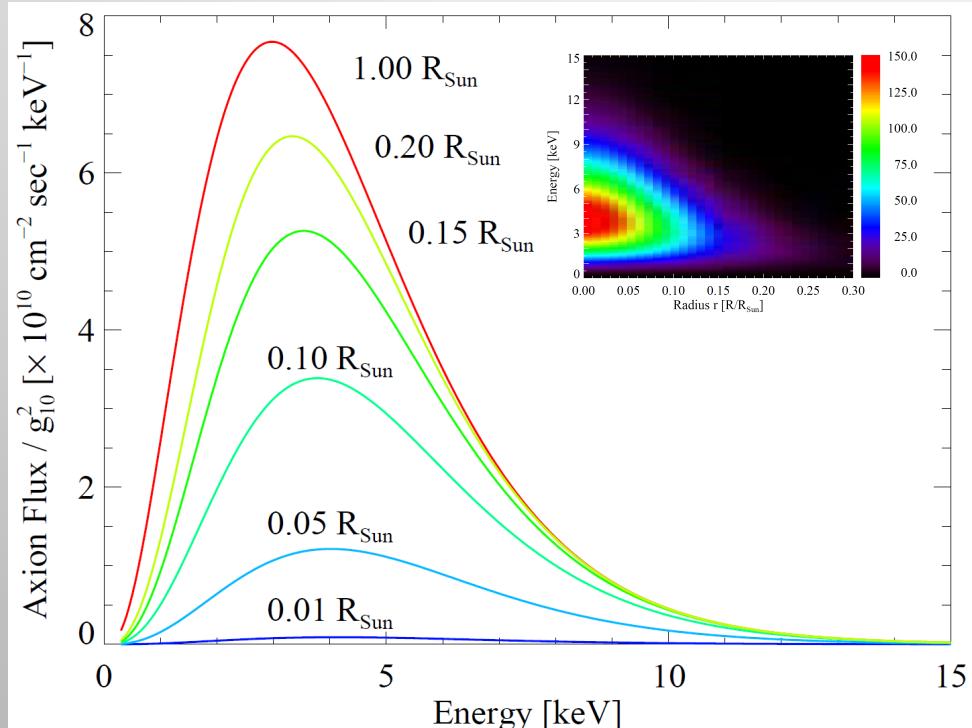
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Hadronic axions from the Sun

▪ Primakoff production of axions in the Sun



Serpico&Raffelt,
based on SSM BP2004 of Bahcall et al.

$$\mathcal{L}_{a\gamma\gamma} = -\frac{C_\gamma \alpha}{8\pi f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} a = -\frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$

- No significant signal observed
- Typical upper limit
- Touching KSVZ benchmark

Expected axion flux from the Sun as function of energy.

→ Solar Physics + Primakoff effect:
only one unknown parameter g_{10}



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Hadronic axions from the Sun

- To date, interpretation of solar axion experimental results has looked at photon-axion coupling: hadronic models

□ Vacuum Phase

$$m_a \leq 0.02 \text{ eV}$$

Phys.Rev.Lett.94:121301, 2005

JCAP 04 (2007) 010

□ ^4He Phase

$$0.02 \text{ eV} \leq m_a \leq 0.39 \text{ eV}$$

JCAP 02 (2009) 008

□ First Results from ^3He Phase

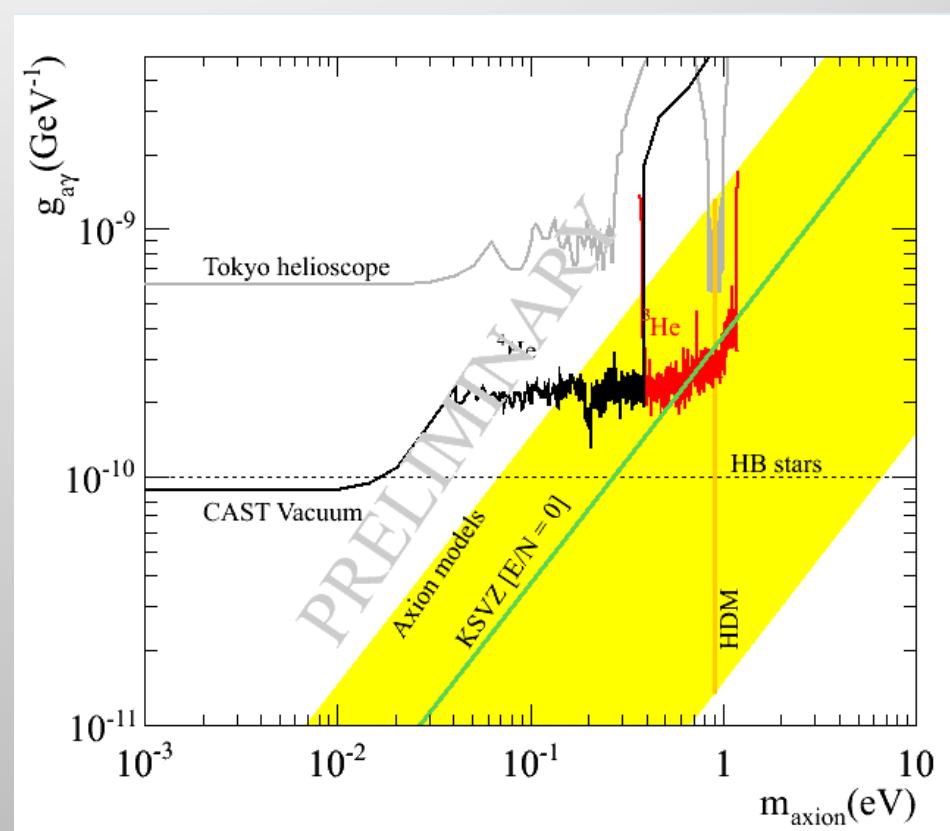
$$0.39 \text{ eV} \leq m_a \leq 0.65 \text{ eV}$$

Phys.Rev.Lett. 107:261302, 2011

□ Preliminary analysis of rest ^3He Phase

$$0.65 \text{ eV} \leq m_a \leq 1.18 \text{ eV}$$

Submitted to PRL [arXiv:1307.1985]



But we know that other processes might be at play ...



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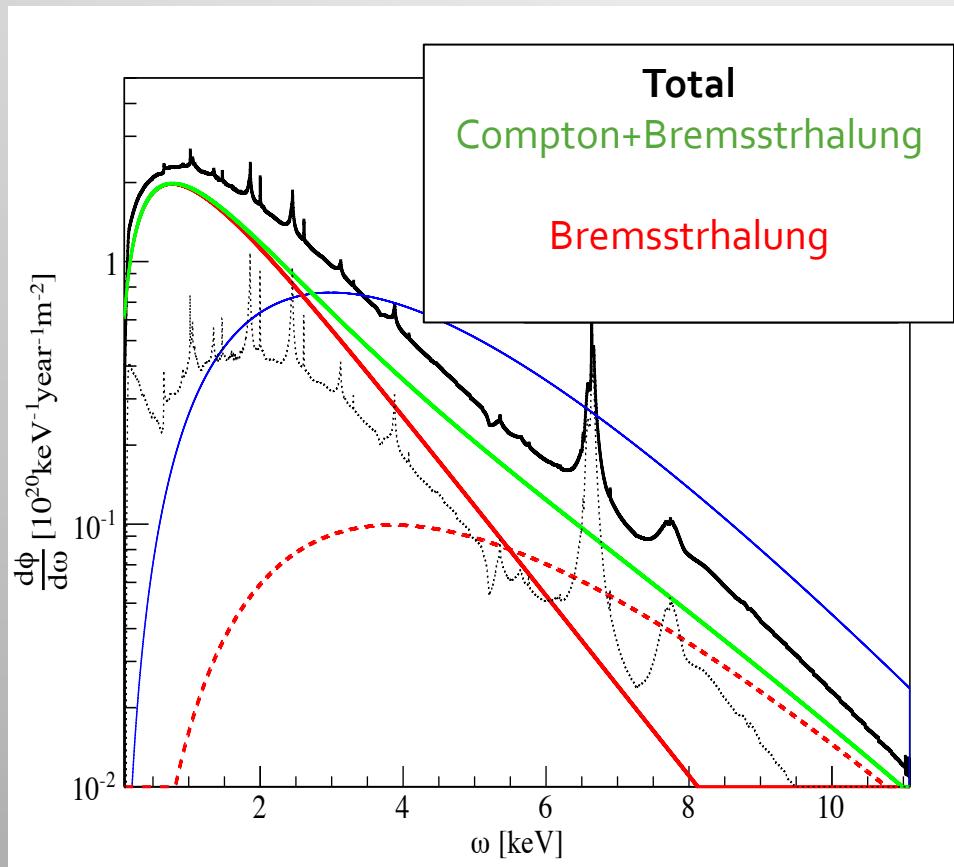
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Non-hadronic axions at CAST

- Primakoff and electron production of axions in the Sun

K. Barth et al., JCAP 05 (2013) 010



$$g_{a\gamma} = 1 \times 10^{-12} \text{ GeV}^{-1}$$

$$g_{ae} = 1 \times 10^{-13}$$

- No significant signal observed
- White Dwarf compatible?

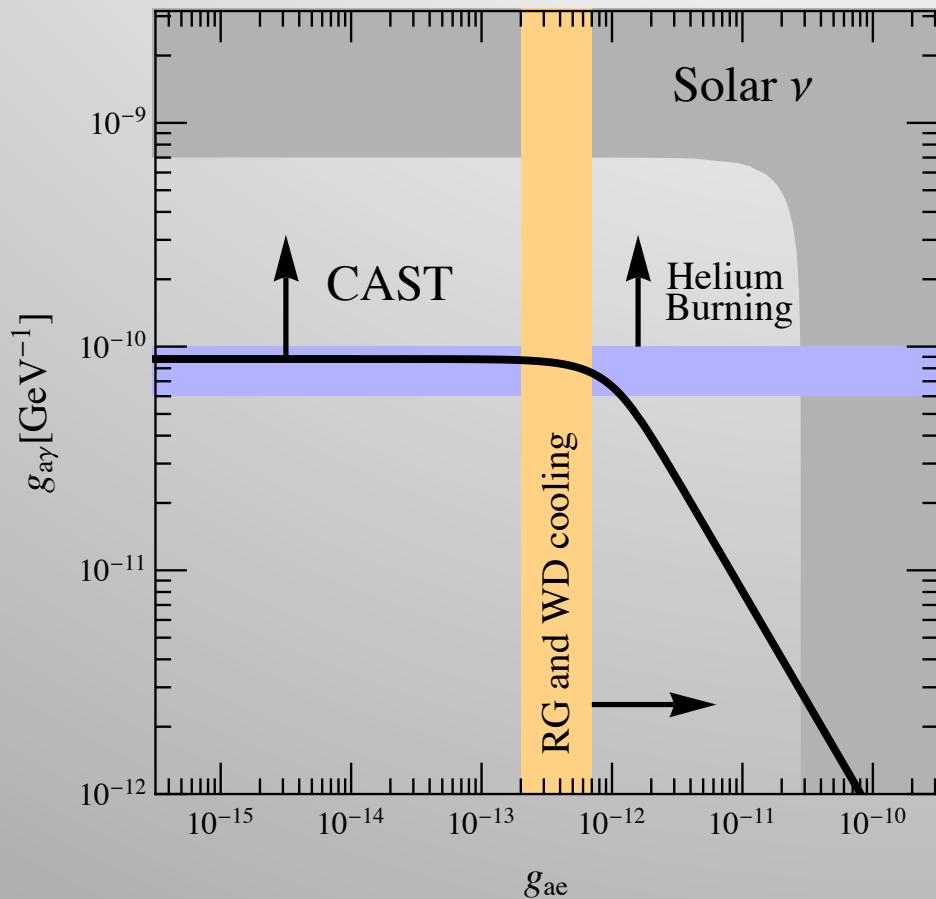
$$\mathcal{L}_{a\gamma\gamma} = -\frac{C_\gamma \alpha}{8\pi f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} a = -\frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$

$$\mathcal{L}_{aee} = C_e \frac{\partial_\mu a}{2f_a} \bar{\psi}_e \gamma_5 \gamma^\mu \psi_e$$

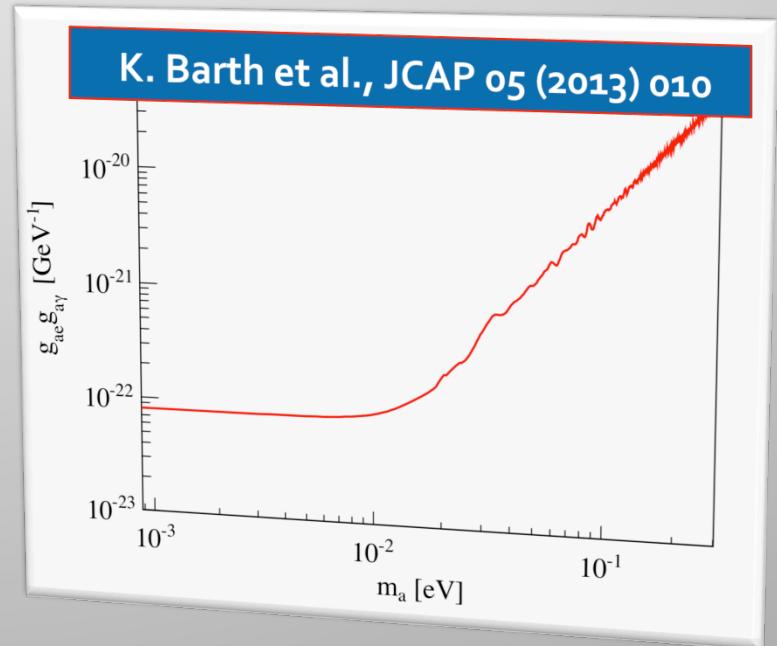
$$g_{ae} = \frac{C_e m_e}{f_a}$$

Axions with CAST

- Extraction of a limit, a generic limit can be expressed as



$$g_{ae} \times g_{a\gamma} \leq 8.1 \times 10^{-23} \text{ GeV}^{-1}$$





Near term future at CAST

- Current CAST science program approved by CERN, runs through 2014
- Schedule for the near future
 - Re-visit ${}^4\text{He}$ phase (2012) and vacuum phase (2013-14):
 - New detectors (lower background, better performance) → higher sensitivity
 - New optics → increased discovery potential
 - Improve present limits
 - Study axion-electron coupling g_{ae}
 - Direct access to DFSZ models
 - Possible access to:
 - Exotica
 - Paraphotons, chameleons, low energy axions



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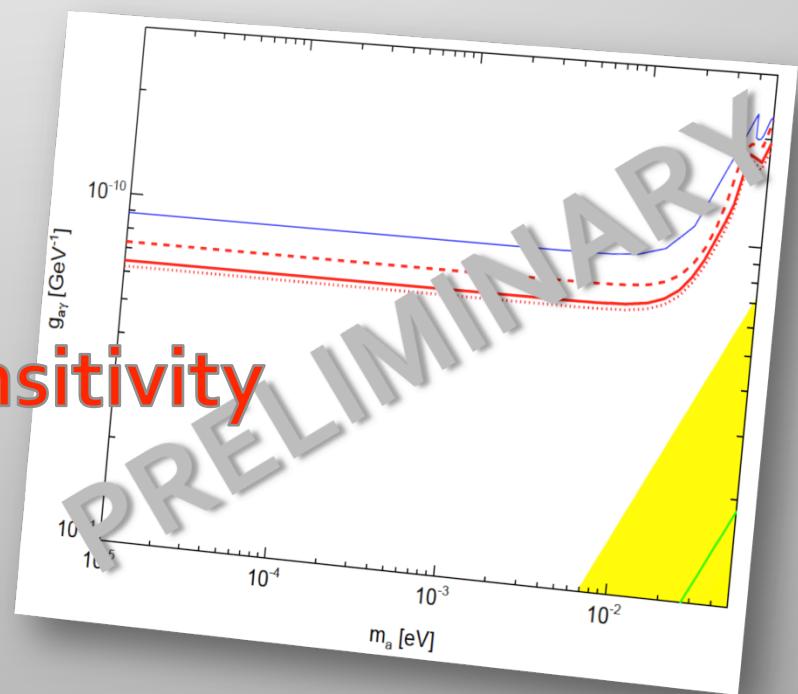
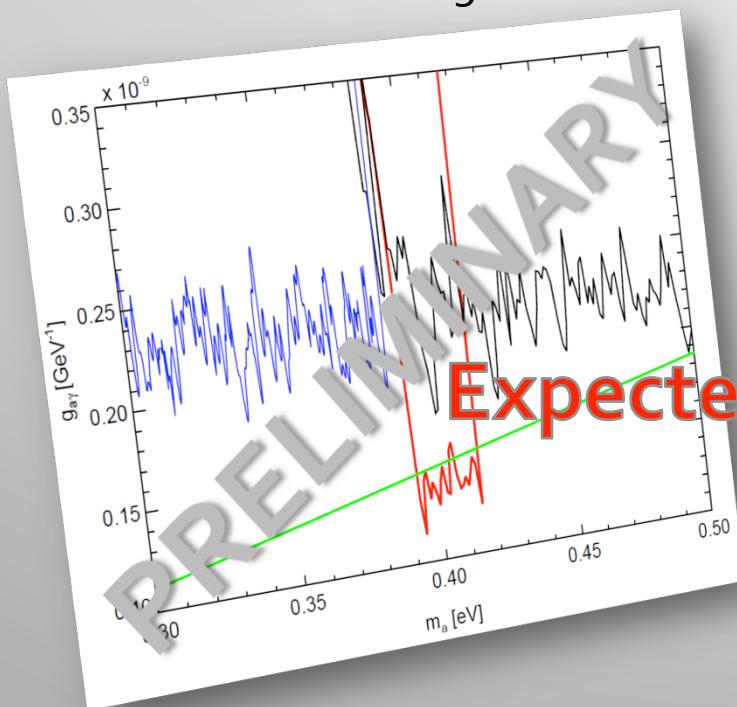
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Near term future at CAST

- Re-visit 4He phase (finished 2012)
- Re-visit vacuum phase (2013-14)
 - Better detectors, new optics → higher sensitivity and increased discovery potential (red line)
 - Probing standard KSVZ model (green line)





IAXO: the next generation axion helioscope



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IAXO “Community”

IAXO	The International Axion Observatory Letter of Intent	Version: 0.4 Date: May 19, 2013 Page 1 of 61
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CERN-SPSC-2013-022 ; SPSC-I-242

Letter of Intent to the CERN SPSC

The International Axion Observatory IAXO

*See Julia K. Vogel
presentation*

F. T. Avignone¹, G. Cantatore², J. M. Carmona³, S. Caspi⁴, S. A. Cetin⁵, F. E. Christensen⁶,
A. Dael⁷, T. Dafni³, M. Davenport⁴, A.V. Derbin⁸, K. Desch⁹, A. Diago³, B. Doebrich²³,
A. Dudarev⁴, C. Eleftheriadis¹⁰, G. Fanourakis¹¹, E. Ferrer-Ribas⁷, J. Galán⁷, J. A. García³,
J. G. Garza³, T. Geralis¹¹, B. Gimeno¹², I. Giomataris⁷, S. Gninenko¹³, H. Gómez^{3,1},
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T. Vafeiadis⁴, K. van Bibber²⁷, P. Vedrine⁷, J. A. Villar³, J. K. Vogel²⁴, L. Walckiers⁴,
W. Wester²⁸, S. C. Yıldız⁵, K. Zioutas²⁹



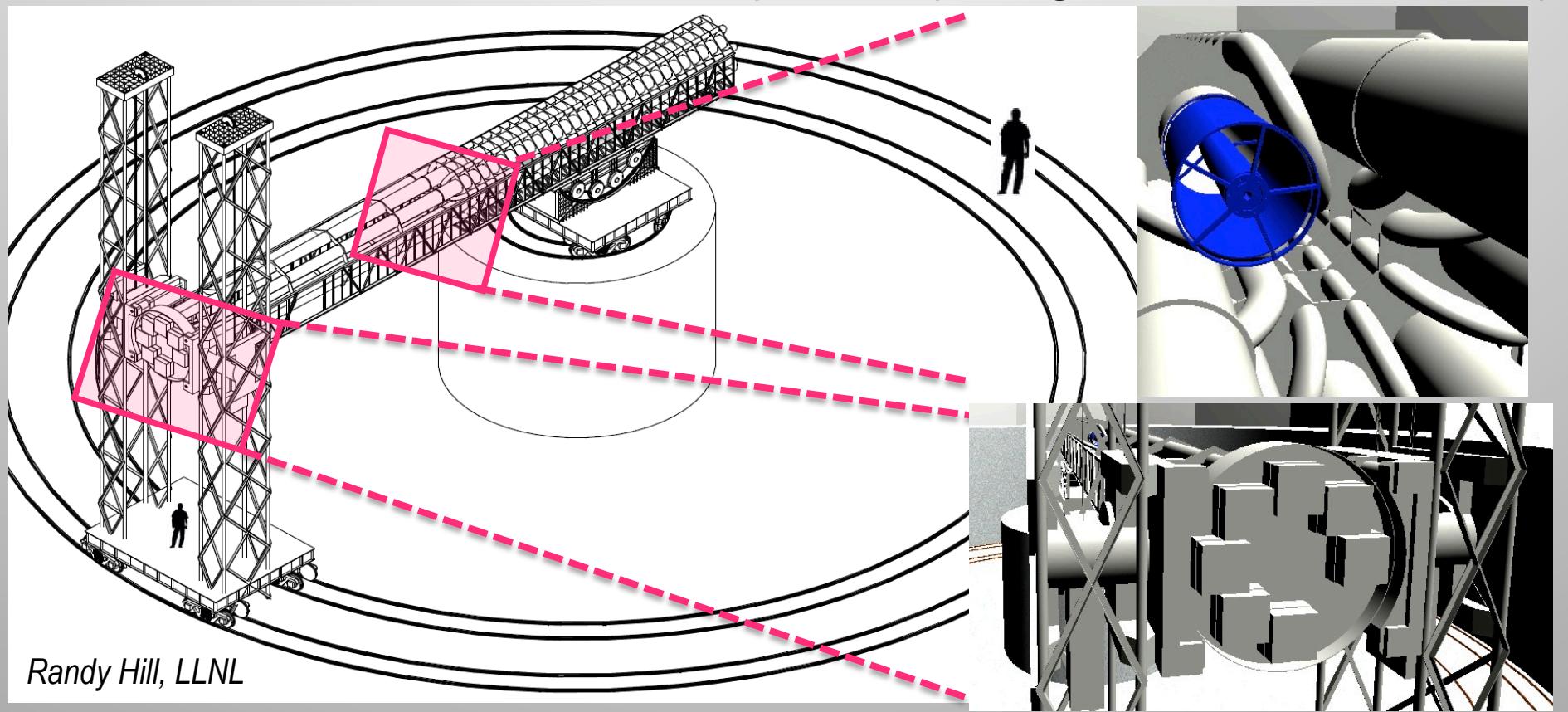
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IAXO: the next generation

- **Challenge:** move a 25-meter long structure (15 m for the magnet, another 10 m for the x-ray telescopes) that weighs 200 tons
- **Solution:** borrow from other heavy-industry and ground-based astronomy



How much beyond CAST we can hope for?

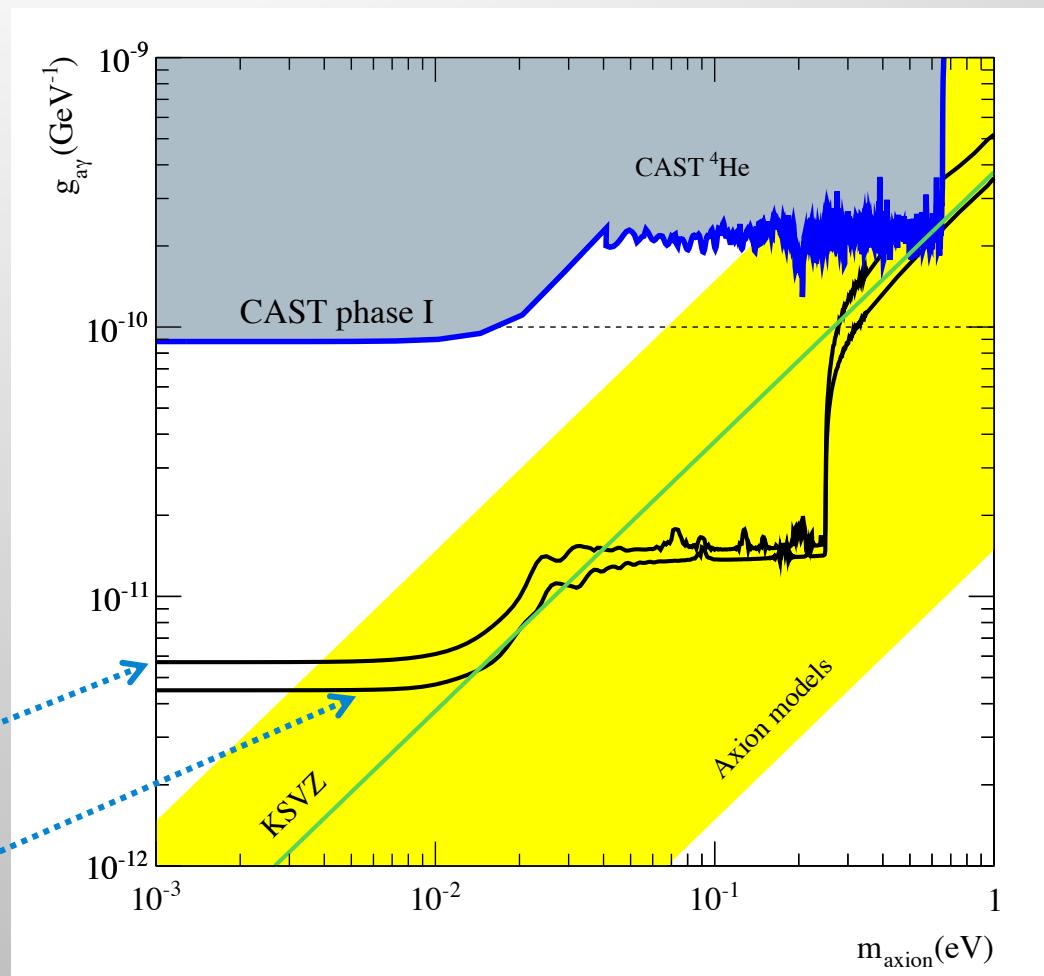


- Factor 8 to 30 better in $g_{a\gamma}$ (4000 to 10^6 in signal strength!!)

Large parts of the QCD favored models could be explored in the coming decade with IAXO

Conservative scenario

Realistic scenario



Irastorza et al. IAXO Letter of Intent



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Prospects for non-hadronic models



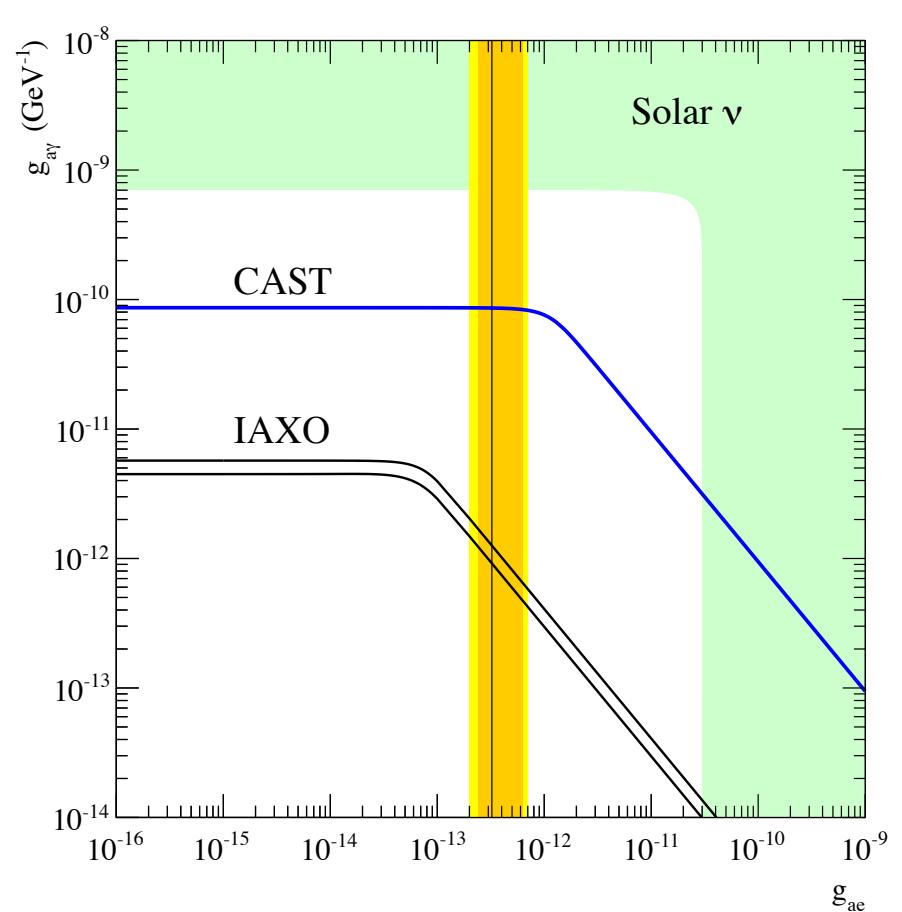
- QCD axions at masses \sim meV seem out of reach even for an improved axion helioscope...

BUT

- Non-hadronic models for axions provide extra axion emission from the Sun through axion-electron compton and bremsstrahlung processes



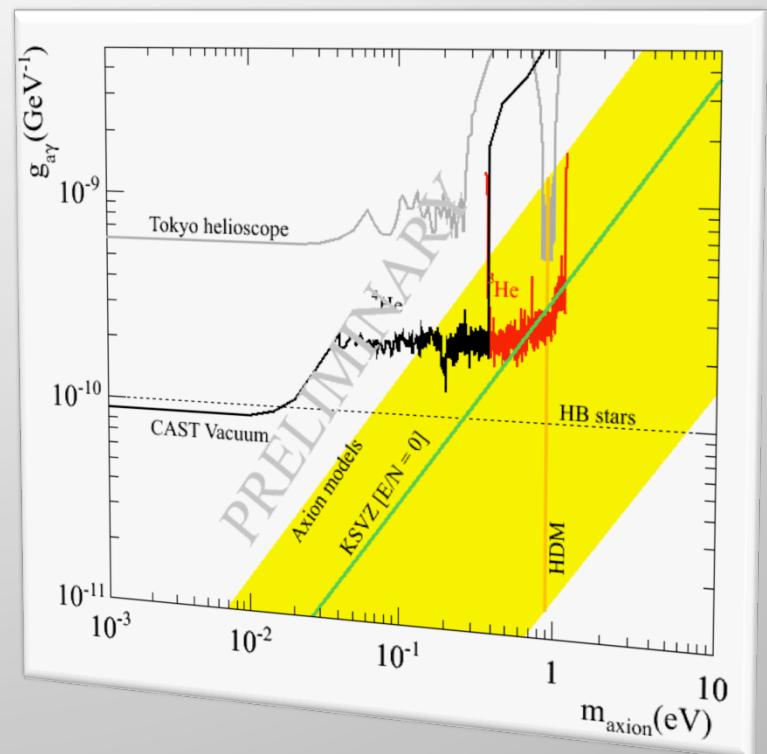
IAXO could improve current CAST sensitivity to non-hadronic axions by about 3 orders of magnitude



Irastorza et al. IAXO Letter of Intent

Conclusions

- CAST has effectively been taking data since fall 2002:
 - CAST PRL2004 most cited experimental paper in axion physics. **Sensitivity** in $g_{a\gamma}$ up to 10^{-10}GeV^{-1} for a wide axion mass range: 0-1.18eV
 - During 2012, CAST revisited axion masses from 0.02 to 0.39 eV with improved sensitivity during 2012.
 - **Ongoing data taking** will set improved limits on solar axion for masses below 0.02 eV
- IAXO is the next generation helioscope.
 - No other technique can realistically improve CAST in the wide axion mass range from 0-1.18eV with $g_{a\gamma}$ sensitivity up to 10^{-12}GeV^{-1}





Thank you!



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Backup slides



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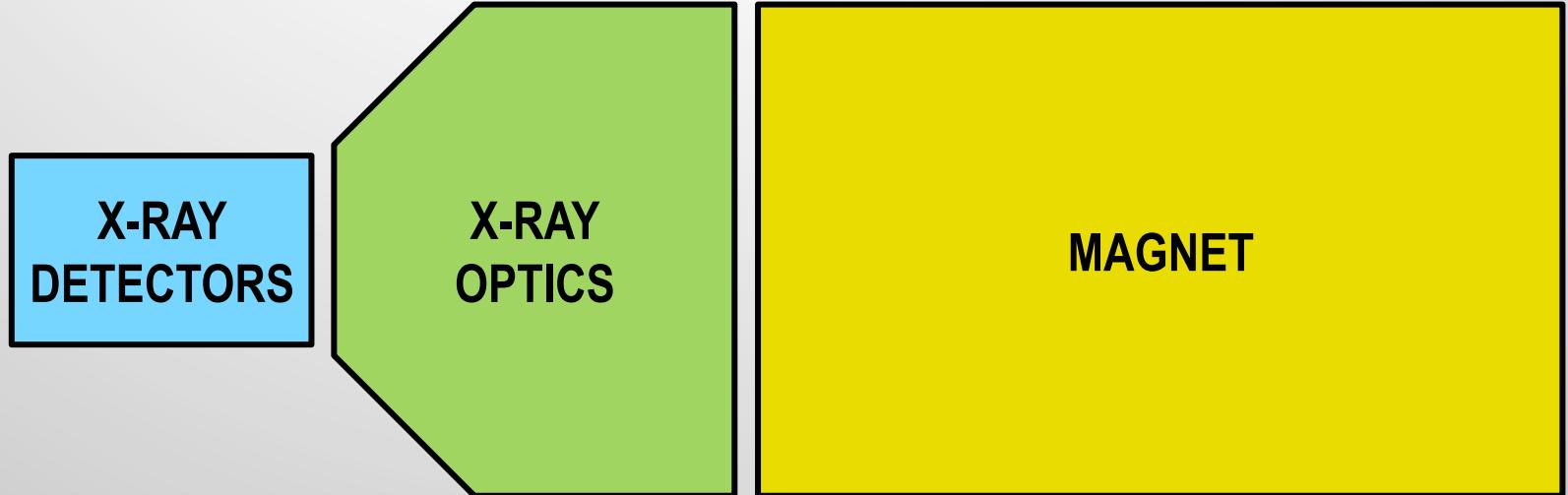
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Three technologies impact sensitivity



$$g_{\text{ay}}^4 \propto \underbrace{b^{1/2} \varepsilon^{-1}}_{\text{detectors}} \times \underbrace{s^{1/2} \varepsilon_0^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2} A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

detectors

b = background

ε = efficiency

optics

s = spot size

ε_0 = efficiency

magnet

B = magnetic field

L = magnet length

A = cross-sectional area

exposure

t = time



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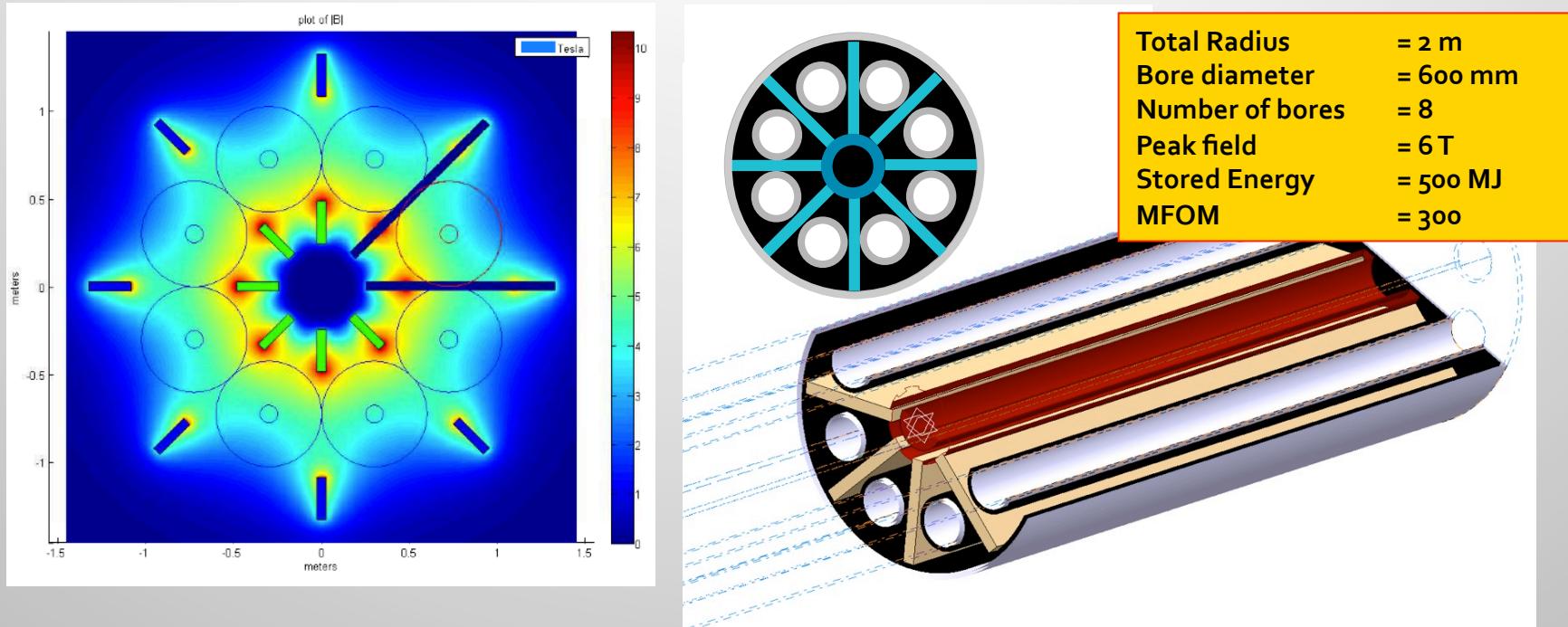
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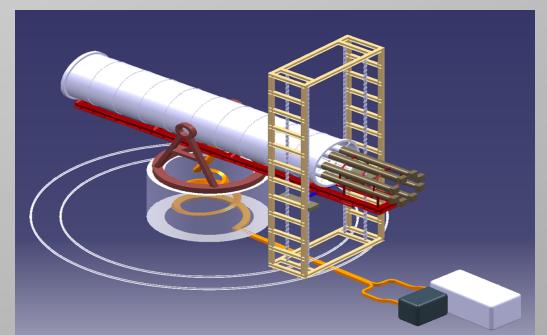
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New Magnet



- CAST has one of the best existing magnets than one can “recycle” for axion physics (LHC test magnet)
- Only way to make a step further is to build a new magnet, specifically conceived for axions.
- Toroidal magnet configuration (ATLAS-like magnet)



New x-ray optics

- X-ray optics are critical to high-sensitivity solar axion experiments, since they greatly reduce the size of the x-ray detector, which in turn, reduces the overall background
- Without an optic, the detector would have to be as large as the magnet bore; with an optic, it is possible to achieve a reduction in area by at least a factor of 100x
- For CAST, the size of the optic is limited by existing, unchangeable physical infrastructure (e.g., exterior walls and support structures)
- We need the ability to construct inexpensive and high-quality optics of various configurations



ABRIXAS flight-spare telescope



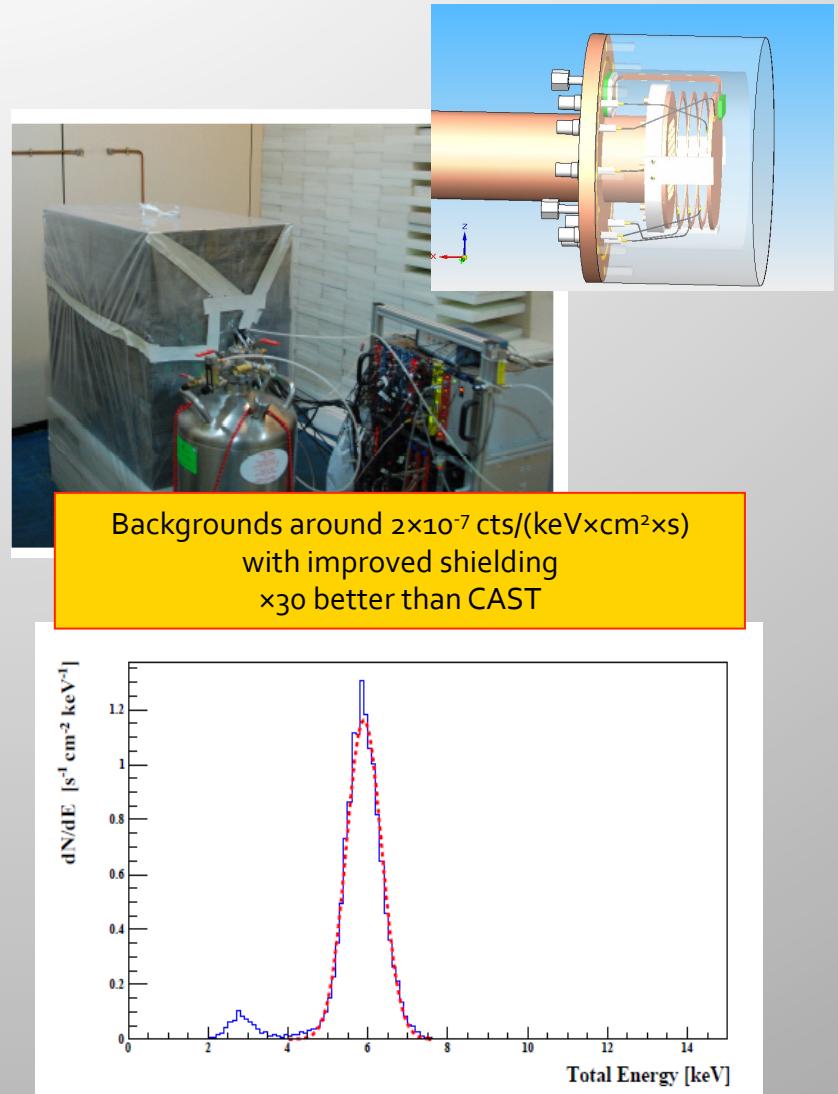
R&D low background detectors

- **Goal:**

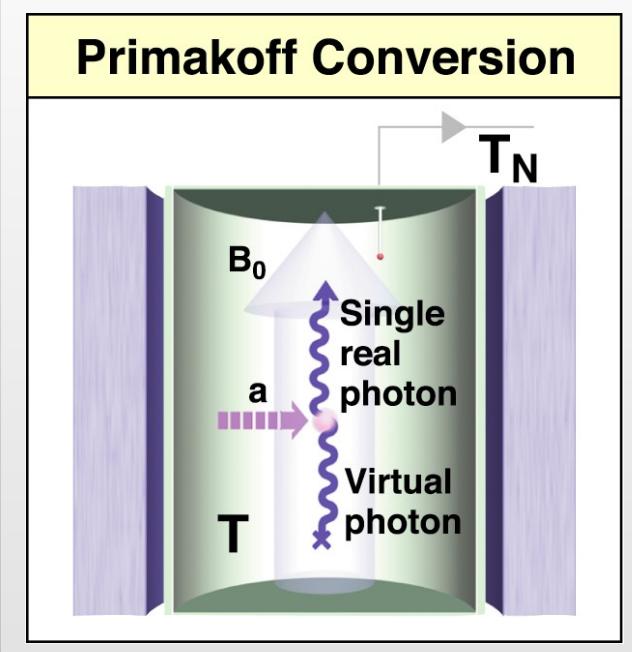
- At least 10^{-7} cts/(keV \times cm 2 \times s), down to 10^{-8} cts/(keV \times cm 2 \times s) if possible

- **Work ongoing:**

- Experimental tests with current detectors at CERN, Saclay & Zaragoza
- Especially: underground setup at Canfranc Underground Lab
- Simulation works to build up a background model
- Design a new detector with improvements implemented



The Haloscope concept



Sikivie *PRL* 51:1415 (1983)

- Dark Matter axions stimulated by a magnetic field, decay into microwave photons which resonate in the cooled cavity and are amplified and read out
- The measurement is enhanced if the photon's frequency corresponds to the cavity's resonant frequency

- **You want:**
 - Large cavity volume
 - High magnetic field
 - High cavity Q
- **You don't want:**
 - Large **thermal noise**
 - High **amplifier noise**

ADMX setup



The radiometer equation dictates search strategy

$$\frac{S}{n} = \frac{P_{sig}}{kT_s} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

* Dicke, 1946

Integration time limited to
~ 100 sec

System noise temp. now

$$T_s = T + T_N \sim 1.5 + 1.5 \text{ K}$$

$$\text{But } T_{\text{Quant}} \sim 30 \text{ mK}$$

HAVE INVESTED HERE!

$$P_{sig} \approx (B^2 V \cdot Q_{cav}) (g_{a\gamma}^2 m_a \rho_a)$$

$$\sim 10^{-23} \text{ watts}$$

But magnet size,
strength $B^2 V \sim \$$



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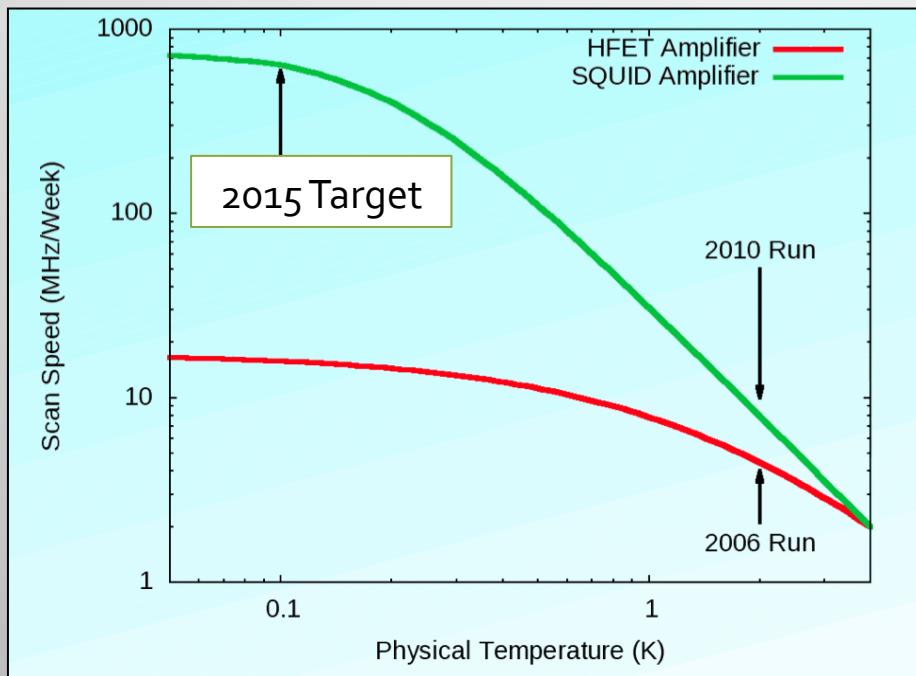
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ADMX cooling

- Cryogenics being design by U. of Florida



Dilution refrigerator will allow to reach much colder temperatures, increasing scanning speed tremendously



Based on Janis 750 model



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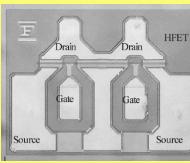
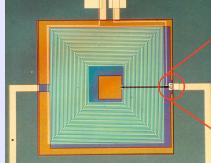
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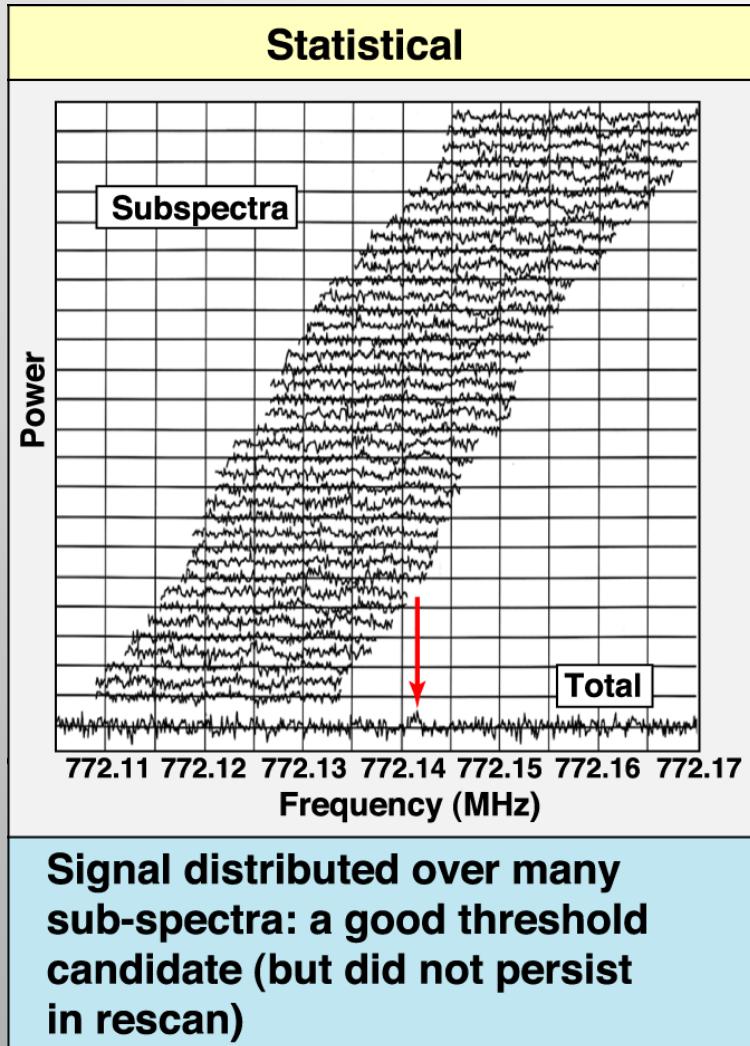
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ADMX phases

<i>Stage</i>	Phase 0	Phase I	Phase II
<i>Technology</i>	HEMT; Pumped LHe 	Replace w. SQUID 	Add Dilution Fridge 
T_{phys}	2 K	2 K	100 mK
T_{amp}	2 K	1 K	100 mK
$T_{sys} = T_{phys} + T_{amp}$	4 K	3 K	200 mK
<i>Scan Rate</i> $\propto (T_{sys})^{-2}$	1 @ KSVZ	1.75 @ KSVZ	5 @ DFSZ
<i>Sensitivity Reach</i> $g^2 \propto T_{sys}$	KSVZ	OR 0.75 x KSVZ	AND! DFSZ



Searching for axions with ADMX



- Cavity resonant frequency is tuned by two movable rods



- Power spectra are measured at each rod configuration
- Axion signal would appear as a constant power excess
- Most backgrounds do not persist



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ADMX results so far

PRL 104, 041301 (2010)

PHYSICAL REVIEW LETTERS

week ending
29 JANUARY 2010

SQUID-Based Microwave Cavity Search for Dark-Matter Axions

S. J. Asztalos,* G. Carosi, C. Hagmann, D. Kinion, and K. van Bibber
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

M. Hotz, L. J Rosenberg, and G. Rybka
University of Washington, Seattle, Washington 98195, USA

J. Hoskins, J. Hwang,[†] P. Sikivie, and D. B. Tanner
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R. Bradley
National Radio Astronomy Observatory, Charlottesville, Virginia 22903, USA

J. Clarke
University of California and Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
 (Received 27 October 2009; published 28 January 2010)

Axions in the μeV mass range are a plausible cold dark-matter candidate and may be detected by their conversion into microwave photons in a resonant cavity immersed in a static magnetic field. We report the first result from such an axion search using a superconducting first-stage amplifier (SQUID) replacing a conventional GaAs field-effect transistor amplifier. This experiment excludes KSVZ dark-matter axions with masses between $3.3 \mu\text{eV}$ and $3.53 \mu\text{eV}$ and sets the stage for a definitive axion search utilizing near quantum-limited SQUID amplifiers.

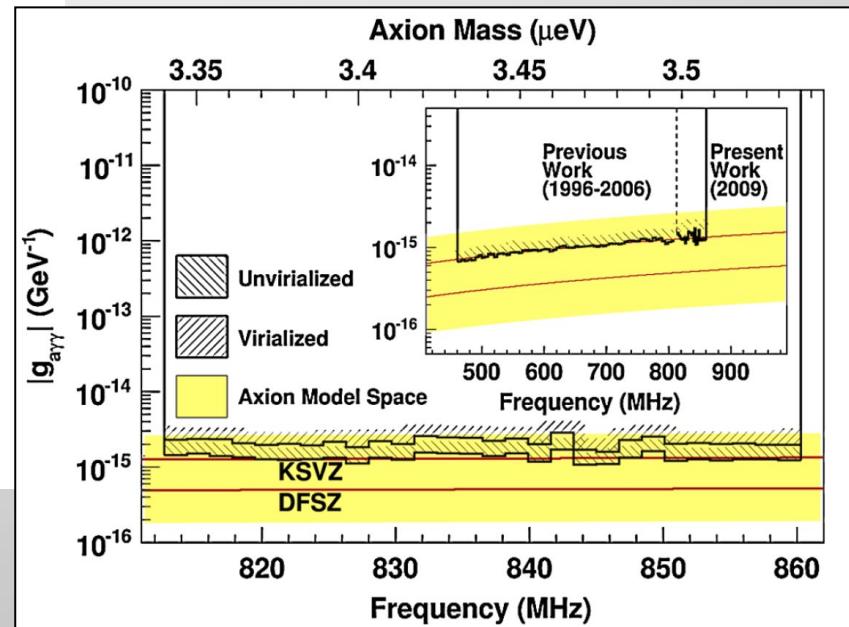
DOI: 10.1103/PhysRevLett.104.041301

PACS numbers: 95.35.+d, 14.80.Va, 95.55.Vj

Covered 812-860 MHz = 48MHz

Total run time: 19 months

Continuous data collecting: 8 months



SQUID Amplifier operational (shielded) in high field region 860-890
 MHz data yields similar limit, publication in progress



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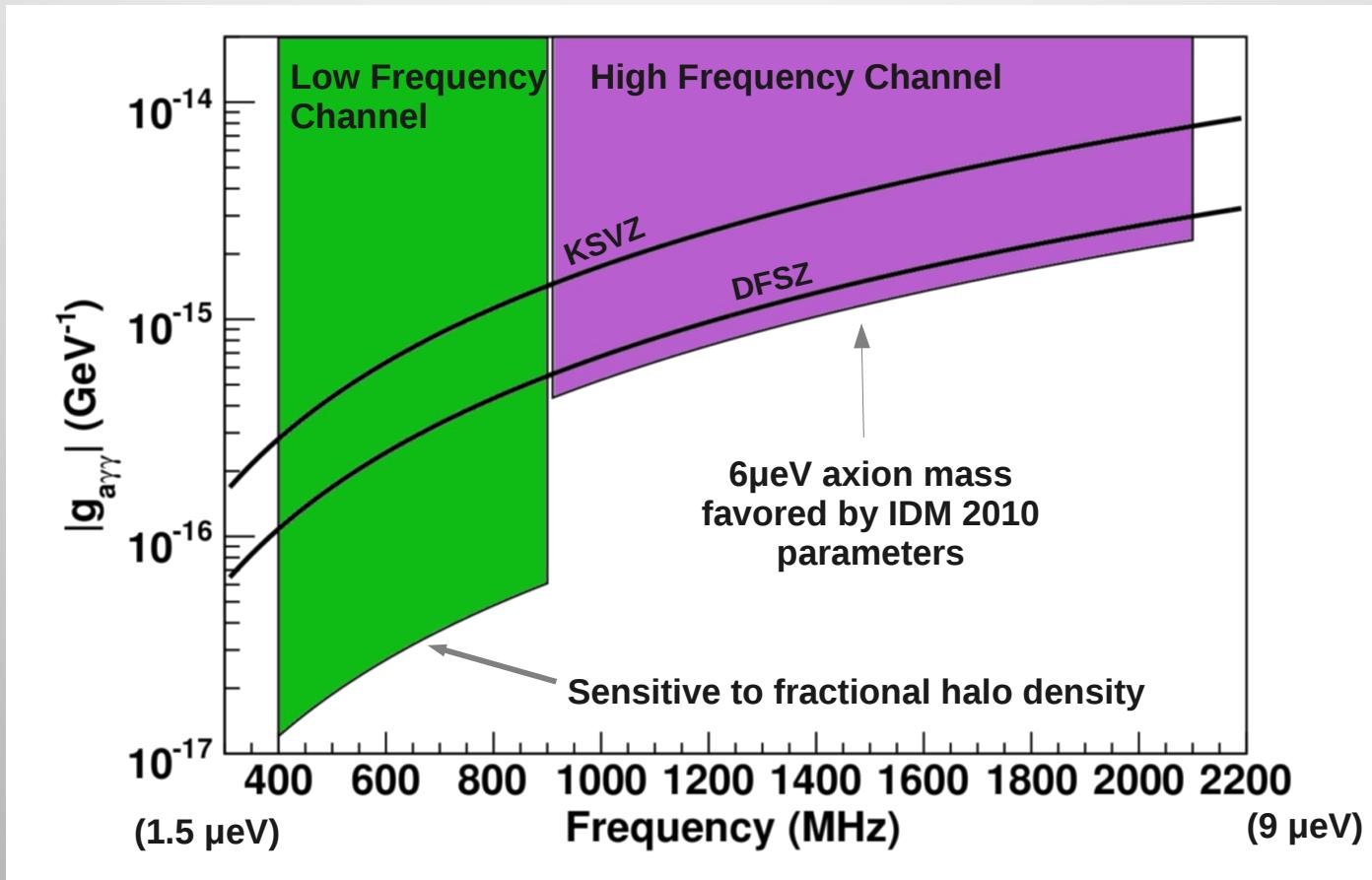
J. Ruz

TAUP 2013

Asilomar, CA.

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ADMX near term goals



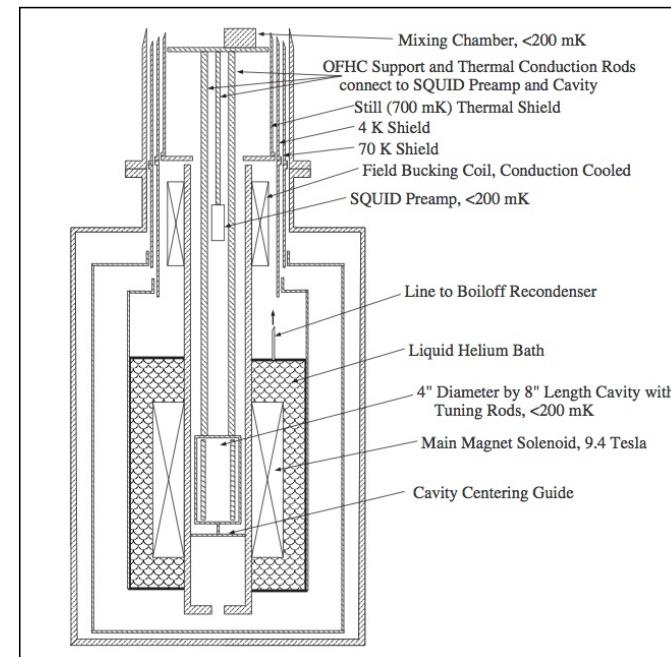
ADMX technology testbed

ADMX – HF: High Frequency – New Collaborator

Second ADMX site: Yale University

PI: Prof. Steve Lamoreaux

- New Superconducting Magnet
5" diameter, 20" long, 9.4 T
- Dilution fridge already in place.



**NSF funded: magnet delivered and tested.
Currently in construction phase.**



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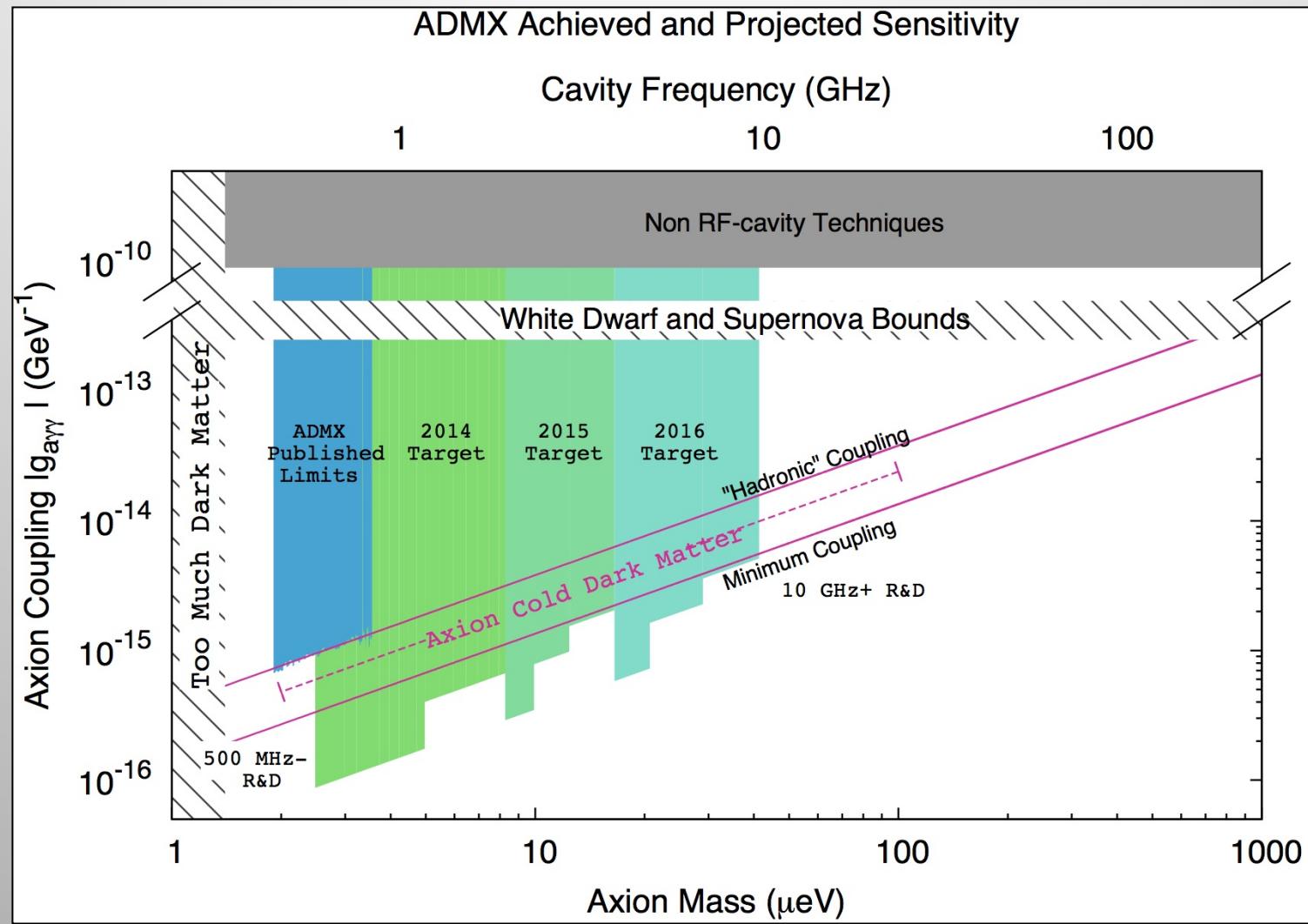
J. Ruz

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ADMX future



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Shining light through the wall

VOLUME 59, NUMBER 7

PHYSICAL REVIEW LETTERS

17 AUGUST 1987

Proposed Experiment to Produce and Detect Light Pseudoscalars

K. Van Bibber

Lawrence Livermore National Laboratory, Livermore, California 94550

N. R. Dagdeviren and S. E. Koonin

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

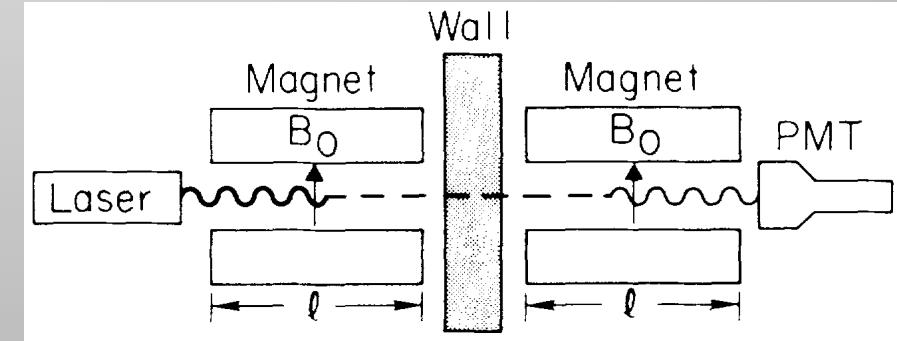
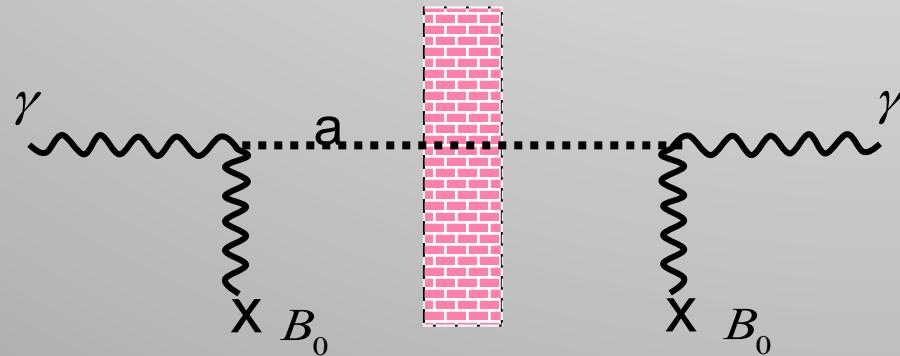
A. K. Kerman

*Center for Theoretical Physics, Department of Physics, and Laboratory for Nuclear Science,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

and

H. N. Nelson

Department of Physics and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305



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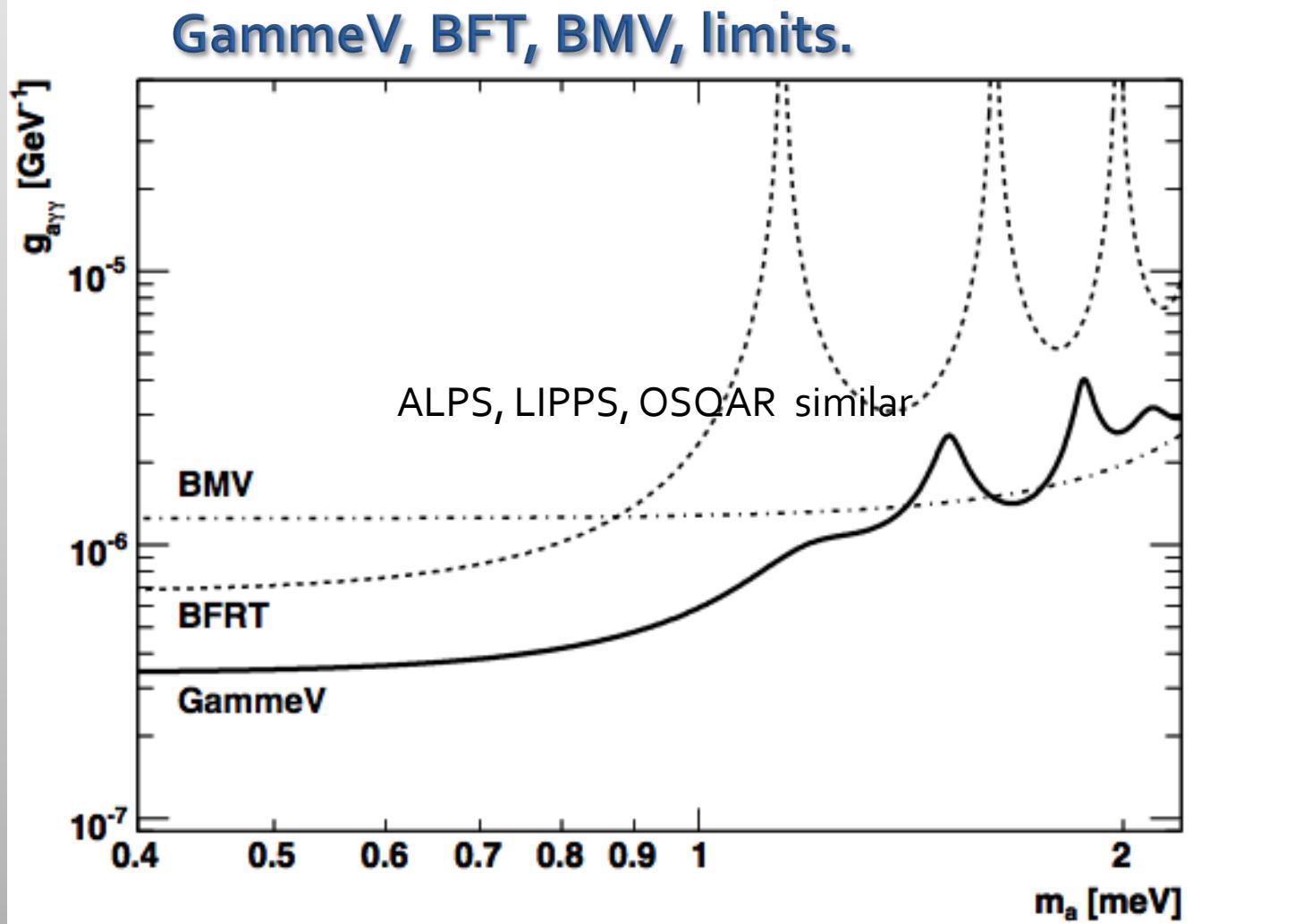
J. Ruz

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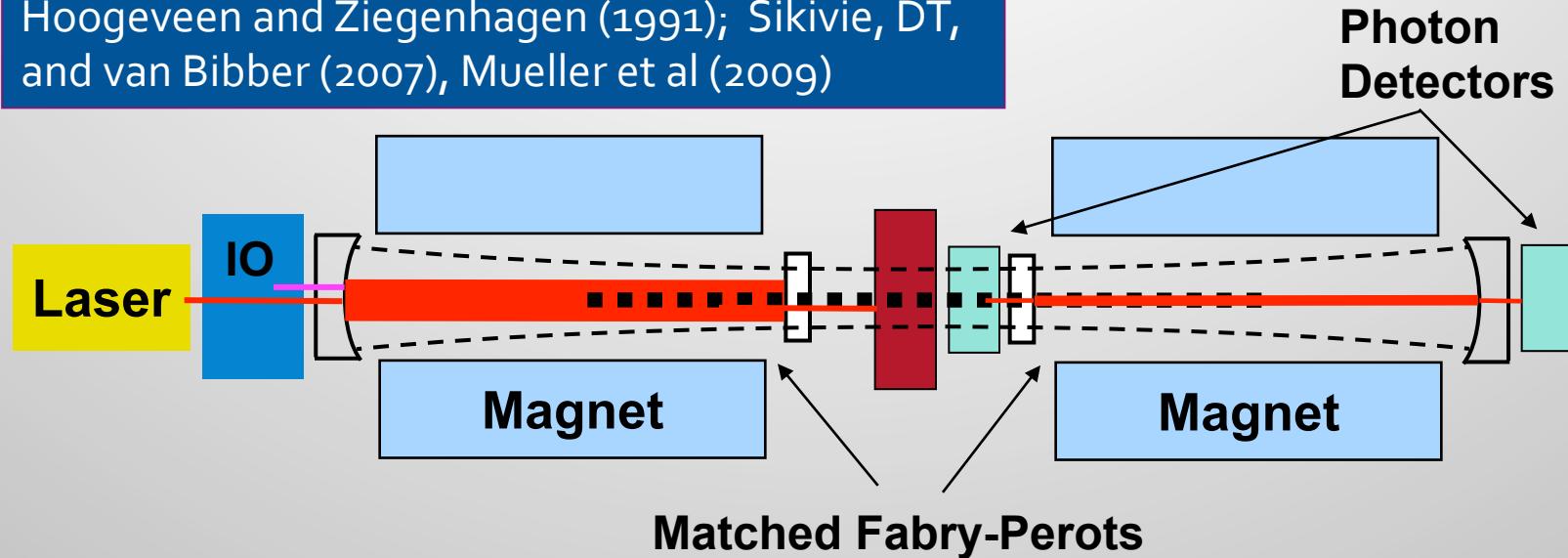
Present limits



ALPS, LIPPS, OSQAR similar

Resonantly enhanced regeneration

Hoogeveen and Ziegenhagen (1991); Sikivie, DT,
and van Bibber (2007), Mueller et al (2009)



Basic concept – use Fabry-Perot optical cavities in both the production and the regeneration magnets.

$$P_{\gamma\alpha\gamma}^{\text{Resonant}} = \frac{2}{\pi^2} FF' \cdot P_{\gamma\alpha\gamma}^{\text{Simple}}$$

where F and F' are the finesse of the cavities. Each could be 10^5

Expected sensitivity

- In the order of CAST limits

